

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

X-644-69-538

PREPRINT

NASA TM X- 63791

APOLLO 11 EVIDENCE FOR THE DIFFERENTIATION OF LUNAR MATERIALS

ROBERT F. MUELLER

DECEMBER 1969



— GODDARD SPACE FLIGHT CENTER —
GREENBELT, MARYLAND

Facility Form 602

Accession Number	(THRU)	(CODE)	(CATEGORY)
N70-15563	1	Q	Q
(PAGES)			
TM-63791			
(NASA CR OR TMX OR AD NUMBER)			

X-644-69-538
Preprint

**APOLLO 11 EVIDENCE FOR THE DIFFERENTIATION
OF LUNAR MATERIALS**

Robert F. Mueller

December 1969

**Goddard Space Flight Center
Greenbelt, Maryland**

X-644-69-538
Preprint

**APOLLO 11 EVIDENCE FOR THE DIFFERENTIATION
OF LUNAR MATERIALS**

Robert F. Mueller

December 1969

**Goddard Space Flight Center
Greenbelt, Maryland**

APOLLO 11 EVIDENCE FOR THE DIFFERENTIATION OF LUNAR MATERIALS

Renewed interest in the problem of our moon's origin has been generated by the first detailed chemical analyses of lunar rocks.¹ I shall here compare these preliminary analyses with the compositions of terrestrial rocks and meteorites and attempt some interpretations in the light of chemical theory.

Although many controversies revolve around the moon's origin, it is reasonable to begin with the hypothesis that this body was originally formed from a gas and dust cloud approximating the solar or "cosmic" composition and that it underwent not only the obvious differentiation with respect to certain gases but also with respect to more refractory elements. It is necessary to consider the possibility that much differentiation could have occurred within the hypothetical solar nebula itself even before separation of the condensed body. One possible mechanism for this type of differentiation is ambipolar diffusion in a mixture of neutral and ionized gases in a magnetic field,² while another mechanism involves differential magnetic forces on solids.³ Differentiation could also have occurred during condensation and agglomeration into the condensed sphere. Finally, further differentiation through igneous and metamorphic processes on such a body are to be expected from theoretical chemical considerations and by analogy with familiar and analogous terrestrial rock and magma types. Discussions of

possible differentiation through magmatic processes have previously been given by Salisbury,⁴ O'Keefe and Cameron,⁵ Lowman,⁶ and Walter.⁷ I shall be concerned not so much with deducing the presence of specific rock types as most of the foregoing authors have, but with making comparisons with Earth's crust as an example of a highly differentiated planetary lithosphere and with understanding how the differentiation processes might be modified in the lunar environment.

A parameter which has been found useful in correlating certain geochemical data is the first ionization potential of an element.⁸ Indeed this parameter also enters directly into the theory of ambipolar diffusion and so should be directly related to possible differentiation in the preplanetary nebular gas. Jokipii has, in fact, shown that the terrestrial abundances of the noble gases can in this way be related to their first ionization potentials.⁹

The chemical compositions of the rocks must also be considered in relation to the history of the entire surface. In general, the data which have accumulated thus far on the processes at work on the moon tend to substantiate the thesis propounded by Baldwin,¹⁰ namely that the surface features, including the circular maria, owe their existence largely to impact explosions of solid bodies varying in kinetic energy. An important corollary which follows from this thesis is that the lunar deposits have been strewn and restrewn across the surface and that they have been disturbed to depths of the order of many kilometers. The extent

to which igneous and other processes have modified this picture of lateral and vertical mixing is as yet unknown but is subject to test by chemical analyses such as these discussed here.

In Figures 1 to 3 are shown plots against the ionization potentials of elemental abundances of the representative lunar samples,¹ Earth's crust¹¹ and the Class I carbonaceous chondrites.¹² In each case the plots are normalized to the elemental abundances of the solar gas,¹² and the abundance of silicon is assumed to be the same in all cases, as is the convention. Although comparing the abundances to the solar gas has the disadvantage of enhancing the lithium peaks artificially, this effect is identical in each case and so does not affect the interpretations. Also the elements Yb and Y, for which some of the lunar specimens were analysed, do not appear in the plots because of uncertainties in their solar abundances.¹² Although results for only four of the 12 lunar analyses are presented, these specimens are entirely representative of the other specimens, and were utilized solely because of their completeness.

Table 1 shows the chemical analysis of a vesicular lunar rock which has been recalculated in terms of normative "minerals" which are in most cases similar to those actually found. This table reflects the high ilmenite content of the rock and indicates that if the ilmenite actually present is close to Fe TiO_3 in composition, the ferromagnesium silicates are only moderately iron rich on the average despite the high total iron content of the rocks. It also shows that

Table 1
Weight Norm of a Vesicular Rock (No. 20) from Tranquility Base¹

Normative Mineral	wt%	
FeTiO ₃ (ilmenite)	23.24	
KAlSi ₃ O ₈ (orthoclase)	0.40	$\frac{\text{Fe}}{\text{Fe} + \text{Mg}}$ (silicates) = 0.33
NaAlSi ₃ O ₈ (albite)	5.08	
CaAl ₂ Si ₂ O ₈ (anorthite)	27.71	
FeCr ₂ O ₄ (chromite)	0.46	$\frac{\text{An}}{\text{An} + \text{Ab}} = 0.84$
ZrSiO ₄ (zircon)	0.20	
Ca (Mg, Fe) Si ₂ O ₆ (ca-pyroxene)	18.66	
(Mg, Fe) SiO ₃ (hypersthene)	23.83	
(Mg, Fe) ₂ SiO ₄ (olivine)	0.43	

the normative anorthite/albite ratio is similar to that actually reported for the observed feldspars.¹ The high normative ilmenite content also has the effect of almost saturating the rock with SiO₂, so that only a small quantity of normative olivine appears. It should be kept in mind however, that the 10 percent uncertainty reported for the chemical analyses¹ will introduce considerable uncertainty into the olivine/pyroxene ratio. However, this uncertainty in the abundances has little effect on the plots of Fig. 1 as may be seen from the size of the crosses.

Perhaps the most significant feature of the diagrams is the great similarity of composition of all the lunar rock types including the fine fraction, which presumably includes at least some dust of diverse origins. It is possible however

that most of the fines are derived from local impacts in Mare Tranquillitatis. Especially marked are the uniform abundances of Ti, Ge, Mg, Ca, and Na. Another significant feature is the qualitative similarity between the distribution patterns of the lunar rocks and Earth's crust (Fig. 2). It is interesting that the parallel holds despite the high crustal abundances of elements with low ionization potentials. However, there are some deviations in this correspondence as for example in the instances of V and Cr.

The abundances of certain of the major constituents such as Ti, Fe and Na differ greatly from their abundances in basalts, which are the most similar common terrestrial rocks in other respects.¹³ Particularly anomalous in terms of terrestrial rocks is the combination of high values of the atomic fraction $\text{Fe}/(\text{Fe} + \text{Mg})$ and low Na. In terrestrial igneous differentiates $\text{Fe}/(\text{Fe} + \text{Mg})$ and the albite content usually increase together and this holds even when absolute iron enrichment occurs.¹⁴

The lack of resemblance between the lunar elementary abundance distributions and that of the Class I carbonaceous chondrites (Fig. 3) is to be expected since the latter are generally regarded as the least differentiated condensed matter known from the solar system.¹⁵ Comparison with the lunar patterns thus immediately indicates that the lunar materials have undergone some differentiation among the refractory elements.

The rocks from Tranquility Base possess such high densities that even in the vesicular rocks this ranges up to 3.4 gm cm^{-3} . It seems likely that the true densities are even higher than this. The fact that these densities exceed the mean

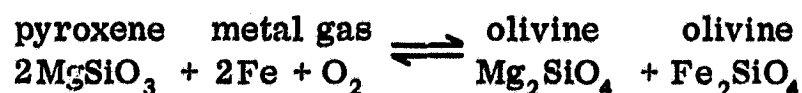
density of the moon (3.33 gm cm^{-3}) points to a differentiation process by which iron is preferentially concentrated in the planet's outer layers. Indeed the gravitational instability which such a situation implies has its parallel on Earth in the differentiated and layered gabbroic bodies such as the Skaergaard¹⁶ complex of east Greenland and the Stillwater¹⁷ complex of Montana. It is possible that in the lunar rocks this effect is accentuated by the high normative ilmenite content. The distribution of iron and magnesium between the ferromagnesian crystals (C) and the melt (L) can be represented by the thermodynamic distribution coefficient D as

$$D = \frac{X_{Fe}^L X_{Mg}^C}{X_{Fe}^C X_{Mg}^L}, \quad (1)$$

where X_{Fe} and X_{Mg} are the atomic fractions of Fe^{2+} and Mg respectively of the total $Mg^{+2} + Fe^{2+}$ in either crystals or melt as indicated by the superscripts. D is a function of the temperature, pressure and composition of the system. In the case of the Stillwater complex¹⁷ the fractionation between the earliest melt, as represented by quenched border facies rocks and the initially precipitated olivine crystals yields $D \sim 4.5$. Similar relations may also be inferred from the Skaergaard complex,¹⁷ so that in the terrestrial differentiated complexes analogous to the lunar rocks, iron is highly concentrated in the melt relative to magnesium as crystallization proceeds. The preliminary Apollo 11 data also point to a similar relation for the Tranquility base rocks if D values are estimated from the olivine phenocrysts and the rock as a whole.

It has been shown experimentally¹⁸ that crystallization in the system MgO-FeO-Fe₂O₃-SiO₂ under anhydrous and reducing conditions leads both to an increase of the Fe²⁺/Mg²⁺ ratio in the melt and to absolute iron enrichment. Operation of the same mechanism in the gabbroic complexes leads to a compositional layering in which the density increases upward in the stratigraphic sequence.¹⁶ Thus the high densities of the lunar surface rocks are not surprising since a partial melting of the lunar layers by any of a number of mechanisms could result in a melt enriched in iron relative to the unmelted residue. Such a melt might well have a density lower than the surrounding solid rock due to considerable expansion on melting,¹⁹ so that it could move to the surface under buoyant forces.

The densities of the lunar rocks are also related to their states of oxidation in a more direct way. Given the observed lunar mineral assemblages of olivine and pyroxene and possible small quantities of metallic iron¹ it is possible to define the oxidation state by the following reaction:



A thermodynamic analysis²⁰ of this reaction shows that the atomic fractions of iron X_{Fe}^{C} of the olivine and pyroxene crystals decrease with the decreasing fugacity of oxygen so that under highly reducing conditions most of the iron would occur in the metallic phase. An analogous reaction which holds in the presence

of magnetite rather than metallic iron shows that under these conditions X_{Fe}^C increases with decreasing oxygen fugacity.²⁰ The small quantities of metallic iron reported for the lunar rocks and the mean density of the moon itself seem to indicate that this body as a whole is not reduced enough to contain much metallic iron.

A major difference between the terrestrial and lunar rocks is the low water content of the latter as is indicated by the lack of hydrous phases. Water has the effect of increasing the solubilities of the feldspars relative to those of the ferromagnesian minerals in the melt so that under high water pressures, such as are attainable on Earth, the melt and the crystallization products tend to be feldspathic.¹⁴ On Earth this process seems to give rise to large volumes of rock belonging to the granite-diorite series which form the bulk of the continental crust and which are reflected in Fig. 2. As previously noted the lunar rocks appear to be more like the relatively anhydrous terrestrial gabbros since they contain large amounts of ferromagnesian minerals. Walter⁷ has already called attention to an analogous effect of low water pressure on the melting properties of the lunar rocks.

The high TiO_2 contents of the specimens from Tranquility base can be accounted for in part by magmatic differentiation of the gabbroic type since this oxide has been observed to increase upward in the Skaergaard complex.¹⁶ It is possible that concentration of TiO_2 in the melt is even more favored under conditions of low oxygen fugacity since this would inhibit its precipitation as

titaniferous magnetite. It is also possible that a relatively small initial difference between the Tranquility base magmatic source rocks and those of terrestrial basalts could be amplified by differentiation.

One inference that may be made regarding the magmas of Tranquility base is that it is unlikely that the Fe-Ti oxides have a liquid immiscibility relation to the silicate melt, for if this were true we should expect a less uniform TiO_2 content than is observed.

In summary, the Tranquility base surface rock compositions appear to be consistent with a differentiation mechanism, perhaps of a complex character embodying igneous and other processes, but which probably contained elements similar to that which produced Earth's crust. However, there are important modifications induced particularly by the low water content of the lunar rocks. This low water content probably inhibited the formation of large volumes of feldspathic rocks. The low absolute values of the Na content of the lunar rocks poses difficulties to any direct comparison with the chondritic meteorites and the source rocks of basaltic magmas. Either the source rocks of the lunar magmas, which presumably lie at depth, were unusually low in sodium or this element was lost by some process such as explosive volatilization. But if the latter process has operated the question arises why there is no significant difference in sodium content between the different rock types. Similarly there seems to be little or no correlation between rock type and the concentration of any other element.

As might be expected, the lunar elemental abundances show no obvious relations to the ionization potentials that might be attributed to differentiation in the preplanetary nebula.⁹ However it is desirable at this point to keep in mind how such processes may have modified the apparently dominant effects of differentiation in the planetary stage.

It is unfortunate that the resemblance in elemental distribution patterns between the lunar rocks and that of Earth's crust cannot yet be used to establish a definite connection between the two planets. It may well be that the moon was separated from Earth by some such mechanism as was recently suggested by O'Keefe.²¹ Certainly the distributions are consistent with such an origin. However it also must be kept in mind that the composition of condensed matter may be similar in quite widely separated regions of the solar system and that this matter might well frequently assume similar configurations on planets in the same size range. It is likely that chemical data from the future Apollo flights will provide an answer to this question.

The writer appreciates interesting discussions with Dr. L. S. Walter.

REFERENCES

1. The Lunar Sample Preliminary Examination Team. *Science*, 165, 1211, (1969).
2. Alfvén, H., "On the Origin of the Solar System," (Oxford University Press, 1954). Hoyle, F. *Quart. J. Roy. Astron. Soc.* 1, 28 (1960).
3. Harris, P. G. and Tozer, D. C., *Nature* 215, 1449, (1967).
4. Salisbury, J. W., *Astrophys. J.* 134, 126, (1961).
5. O'Keefe, J. A. and Cameron, W., *Icarus* 1, 271, (1962).
6. Lowman, P. D., Jr., *Icarus*, 1, 35, (1963).
7. Walter, L. S., *Ann. New York Acad. Sci.*, 123, 470, (1965).
8. Ahrens, L. H., *Geochim et Cosmochim. Acta* 3, 1, (1952).
9. Jokipii, J. R., *Icarus* 3, 248 (1964).
10. Baldwin, R. B., "The Face of the Moon," Univ. Chicago Press, (1949) and "The Measure of the Moon," Univ. Chicago Press (1963).
11. Ahrens, L. H. and Taylor, S. R., "Spectrochemical Analysis," Addison-Wesley, Reading, Mass. (1961).

Aller, L. H., "The Abundance of the Elements," Interscience, New York, (1961).
12. Gloes, G. G., Chapt. 5, Cosmic Abundances in "Handbook of Geochemistry," VI (K. H. Wedepohl, ed.) Springer, Berlin, (1969).

13. Nockolds, S. R., Bull. Geol. Soc. Am. 65, 1007, (1954).
14. Mueller, R. F., NASA TN D-5400, (1969).
15. Ringwood, A. E., Rev. of Geophys. 4, 113, (1966).
16. Wager, L. R., and Deer, W. A., "Geological Investigations in East Greenland — Pt. III. The Petrology of the Skaergaard Intrusion, Kangerdlugssuag, East Greenland," Medd. om Grønland, 105, No. 4, (1939).
17. Hess, H. H., "Stillwater Igneous Complex, Montana," Geol. Soc. Am. Memoir 80, (1960).
18. Muan, A., and Osborn, E. F., Jour. Am. Ceramic Soc. 39, 121, (1956).
19. Birch, F., Schairer, J. F., and Spicer, H. C., "Handbook of Physical Constants," Geol. Soc. Am. Spec. paper 36, (1942).
20. Mueller, R. F., Geochim. et Cosmochim. Acta, 29, 967, (1965).
21. O'Keefe, J. A., Jour. Geophys. Res., 74, 2758, (1969).

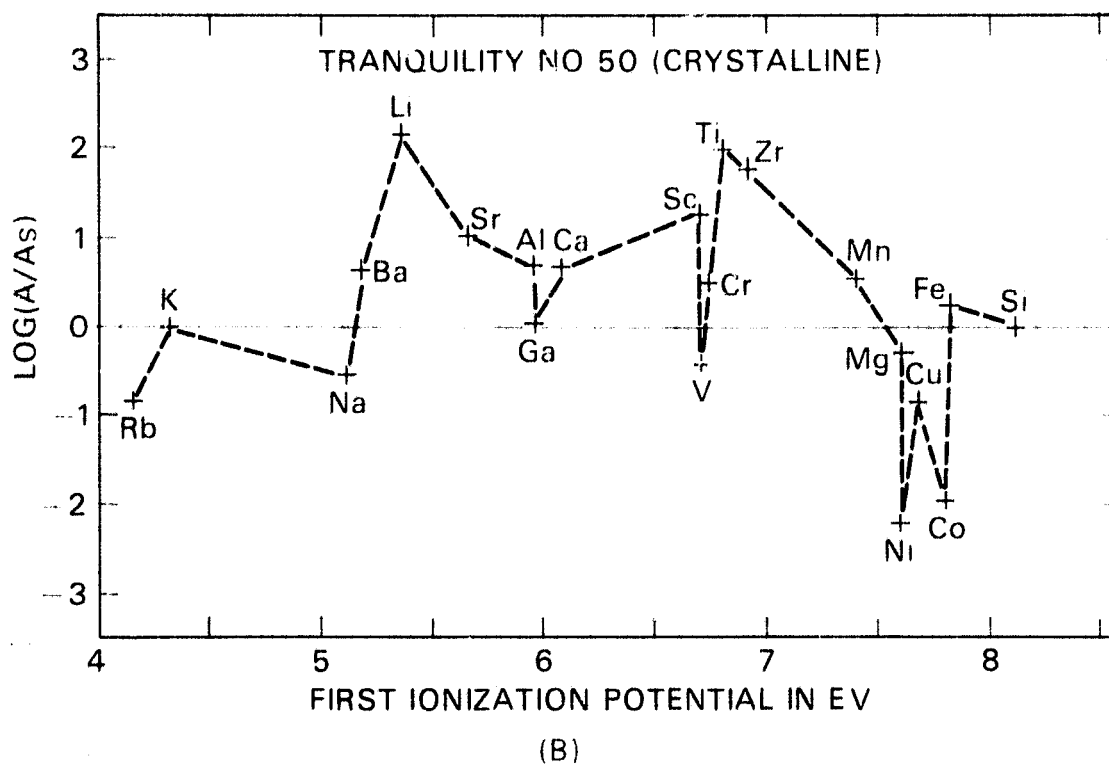
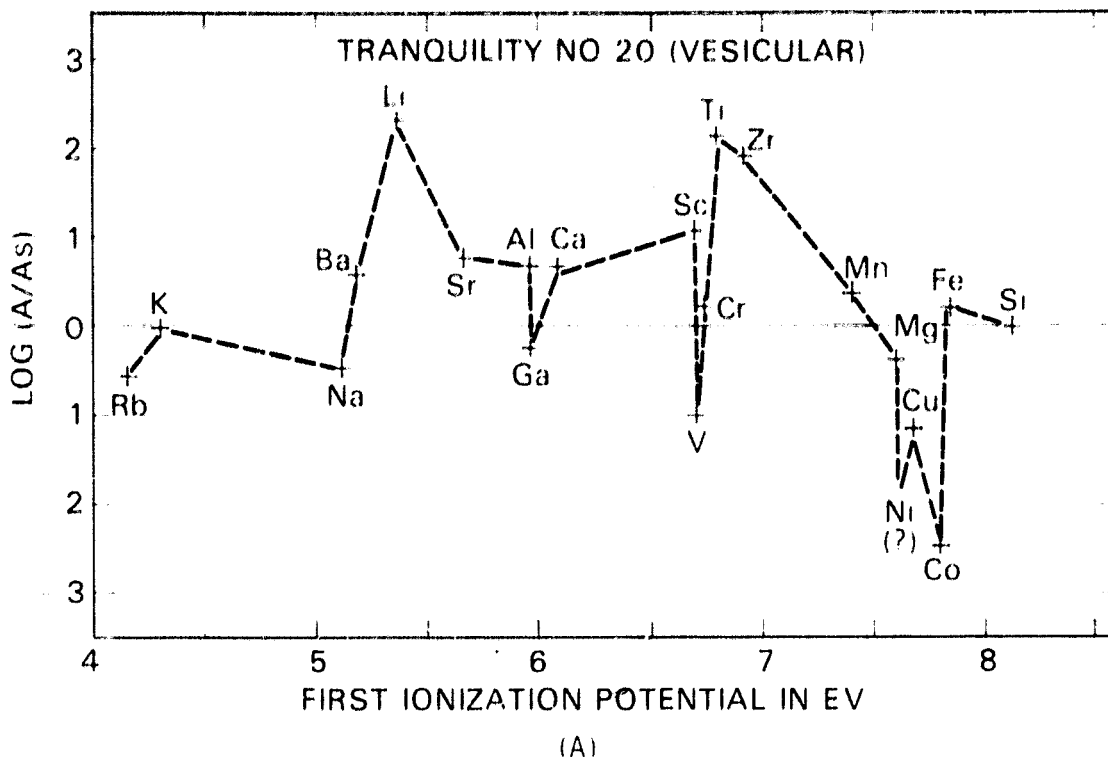
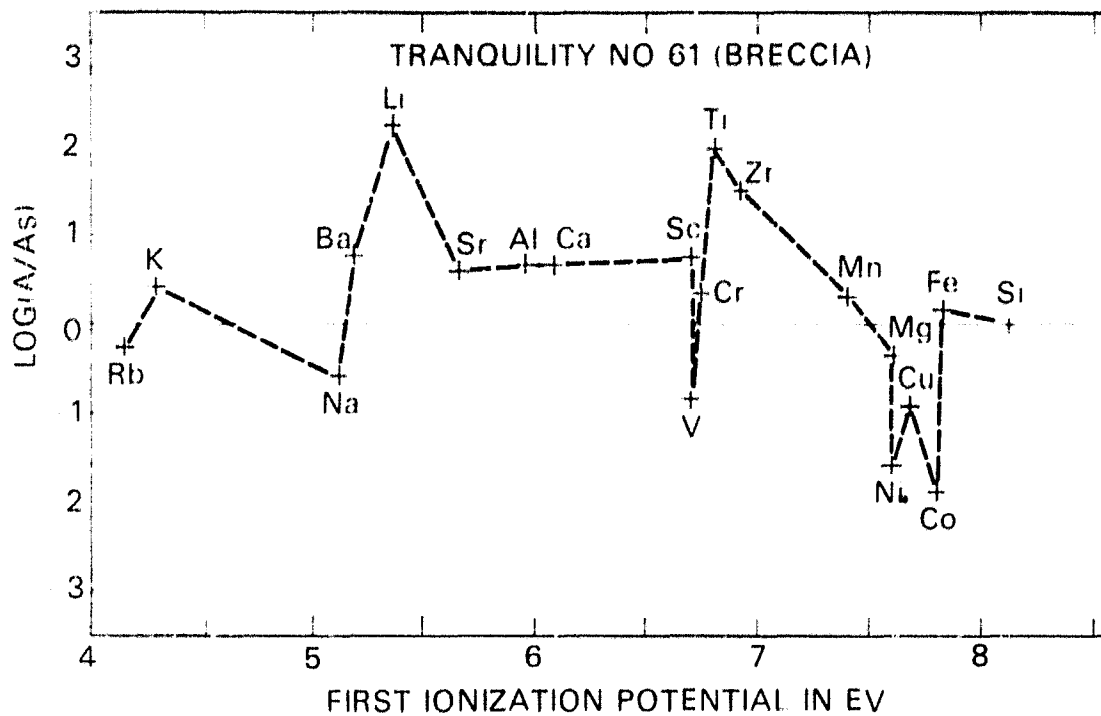
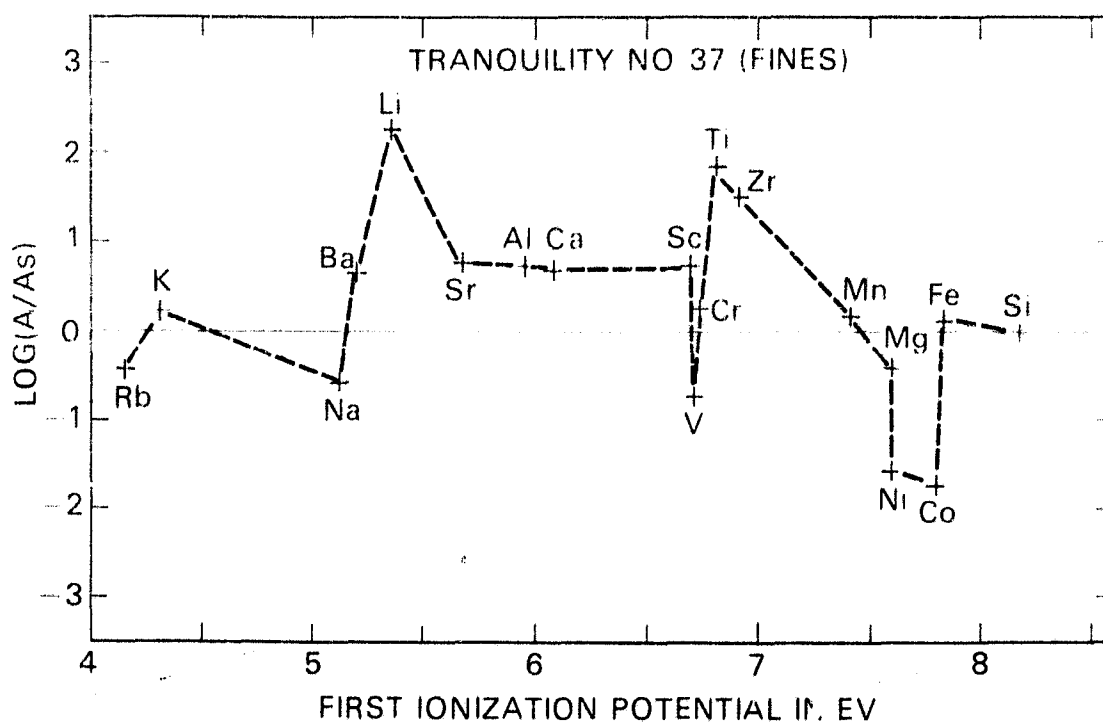


Figure 1—Normalized logarithms of the elemental abundances of the major lunar rock types¹ of Tranquility Base plotted against the first ionization potentials. A indicates the lunar elemental abundances. As indicates the solar elemental abundances to which the A values are normalized. The size of the crosses correspond to 10 percent uncertainty in the chemical analyses.



(C)



(D)

Figure 1—Normalized logarithms of the elemental abundances of the major lunar rock types¹ of Tranquility Base plotted against the first ionization potentials. A indicates the lunar elemental abundances. As indicates the solar elemental abundances to which the A values are normalized. The size of the crosses correspond to 10 percent uncertainty in the chemical analyses. (Continued)

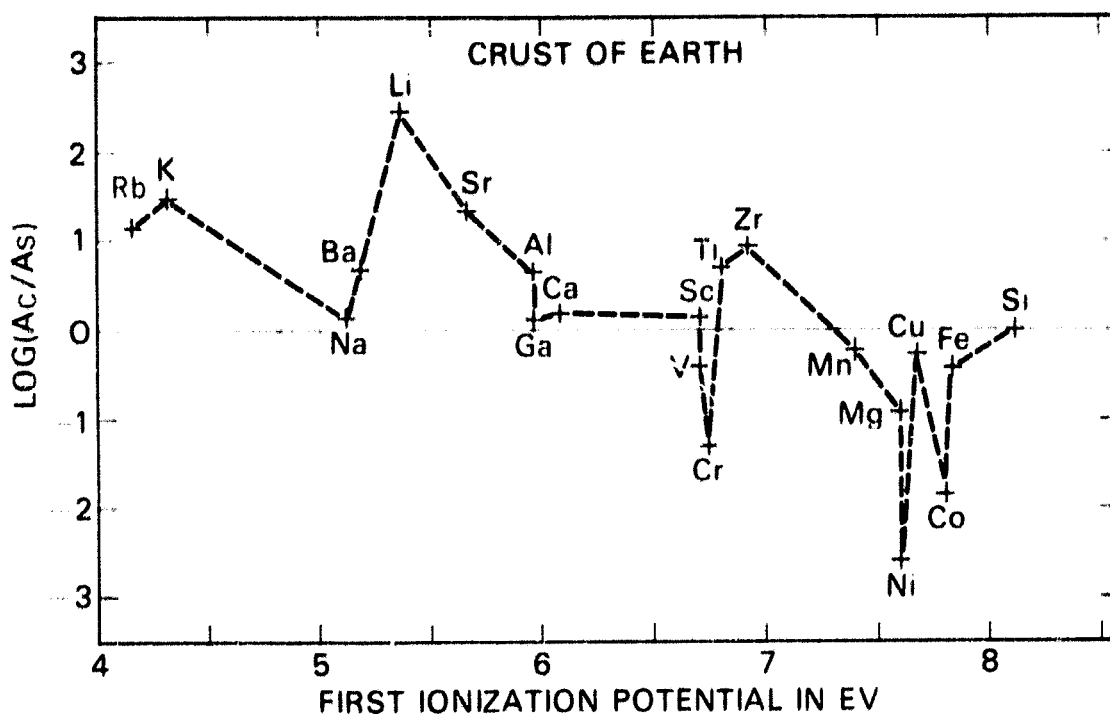


Figure 2—Normalized logarithms of the elemental abundances in Earth's crust¹¹ plotted against the first ionization potentials. Ac indicates the crustal elemental abundances. As indicates the solar elemental abundances to which the Ac values are normalized.

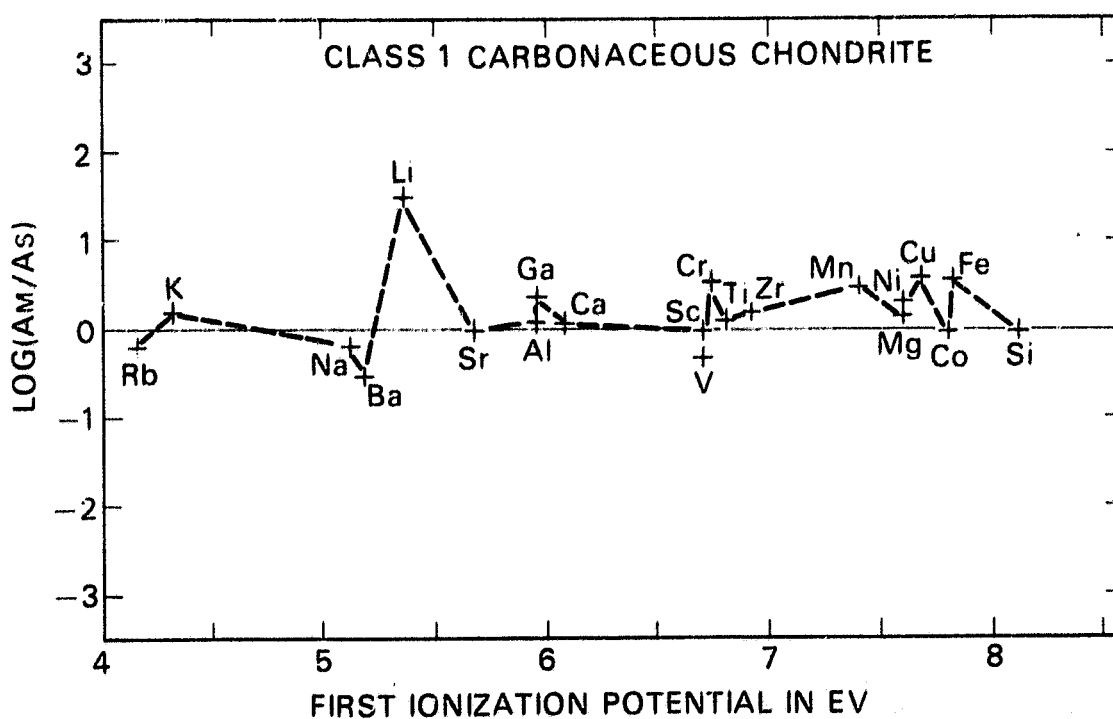


Figure 3—Normalized logarithms of the elemental abundances of the Class I carbonaceous chondrites¹² plotted against the first ionization potentials. Am indicates the meteorite abundances. As indicates the solar elemental abundances to which the A_M values are normalized